# Midterm Project (25 points)

Elementary Particle Physics

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## Overview

In this one-week project you will reproduce, in a simplified form, the basic strategy used in many particle discoveries: the identification of a *resonance* via a peak in the *invariant mass* distribution of its decay products.

You will be given a dataset of simulated two-body decays, generated from a *real* hadronic resonance with mass and width close to the values quoted in the Review of Particle Physics (PDG). Your task is to reconstruct the invariant mass, identify whether a resonance is present, estimate its parameters, and interpret your findings in light of what you have learned about relativistic kinematics, symmetries and resonances.

The project is divided into three parts:

- Part 1: Background reading and short conceptual questions.
- Part 2: Data analysis and numerical computation.
- Part 3: A short scientific report (2–3 pages).

**All three parts are mandatory**.

## Background reading

Before starting the analysis, read carefully:

1. D. Griffiths, *Introduction to Elementary Particles* (2nd, revised edition):
   - Chapter 1 (historical introduction) – for context.
   - Chapter 3 (Relativistic kinematics) – four-vectors, invariant mass, two-body decays and scattering.
   - Chapter 4 (Symmetries) – to recall the role of Lorentz invariance and conservation laws.
2. Review of Particle Physics (PDG), available online at `pdg.lbl.gov`:
   - The **"Kinematics"** review (currently section titled *Kinematics*), which summarizes the general formulas for two-body decays and invariant mass.

- The **"Resonances"** or related review on resonance parametrizations and Breit–Wigner line shapes.
- The relevant entries in the particle listings (to compare your extracted mass and width with PDG values).

You are encouraged (but not required) to consult additional sources (lecture notes, review articles) if you find them helpful.

# Part 1: Conceptual preparation

Answer the following conceptual questions in your own words. Each answer should be about 3–6 sentences, clear and to the point.

1. Why is the invariant mass
$$M^2 = (p_1 + p_2)^2$$
the natural quantity to reconstruct a new particle from its decay products? Explain the role of Lorentz invariance.

2. What is a resonance? Describe the physical meaning of a peak in the invariant mass spectrum in terms of an unstable intermediate state.

3. What is the qualitative connection between the resonance width $\Gamma$ and the lifetime $\tau$ of an unstable particle? Explain why a narrow peak corresponds to a relatively long-lived state.

4. Why does the observation of a localized peak in the invariant mass distribution of a given final state strongly suggest the existence of a new particle? Mention the assumptions that go into this statement.

Submit these answers as a short PDF or as the first section of your final report.

# Part 2: Data analysis and numerical computation

## Dataset

Each student will receive a CSV file named,

`dataset_Name.csv`,

Each row corresponds to one two-body decay event of the form

$$X \to a + b,$$

and contains the measured three-momenta and rest masses of the daughter particles in natural units (GeV):

`eventID, px1, py1, pz1, px2, py2, pz2, m1, m2`

The events are generated in the rest frame of the parent particle $X$ with an isotropic decay, plus a background sample of random two-particle events. The parent particle $X$ is chosen to have mass and width close to a known resonance in the PDG tables, but the decay channels are simplified for the purposes of this exercise.

You may use any computational tool you like (e.g. Python, Julia, C++, Matlab, etc.), as long as your steps are clearly documented and reproducible.

## Task 2.1: Event-by-event invariant mass

For each event:

1. Compute the magnitude of each three-momentum:

$$p_i^2 = p_{xi}^2 + p_{yi}^2 + p_{zi}^2, \qquad i = 1, 2.$$

2. Compute the energies of the two particles:

$$E_i = \sqrt{p_i^2 + m_i^2} \quad \text{(natural units } c = \hbar = 1\text{)}.$$

3. Compute the invariant mass of the pair:

$$M = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2},$$

where

$$(\vec{p}_1 + \vec{p}_2)^2 = (p_{x1} + p_{x2})^2 + (p_{y1} + p_{y2})^2 + (p_{z1} + p_{z2})^2.$$

**Deliverables for Task 2.1:**

- A table with the first 10 computed invariant masses $M$ (in GeV).
- Your code with clear comments describing the computation procedure.

## Task 2.2: Invariant mass histogram

Construct a histogram of the invariant mass $M$. Choose a reasonable mass range (for example from 0.5 GeV to 3.0 GeV, depending on your dataset). Use about 40–60 bins so that you can see structure but still have reasonable statistics per bin.

Label the axes clearly. Horizontal axis with "Invariant mass $M$ (GeV)" and vertical axis with "number of events per bin".

**Deliverables for Task 2.2:**

- The histogram as a figure (in PDF that will be embedded in your report).
- A short explanation of how you chose the bin width and range.

## Task 2.3: Resonance identification and parameter extraction

Inspect your invariant mass histogram:

1. If you observe a visible peak, estimate:
    - The resonance mass $M_0$ (position of the maximum).
    - The width $\Gamma$ (for example, the full width at half maximum).

2. Convert the width into an approximate lifetime:

$$\tau \approx \frac{\hbar}{\Gamma}.$$

   Use $\hbar \simeq 6.58 \times 10^{-25}\,\mathrm{GeV}\cdot\mathrm{s}$.

3. If your histogram does *not* show a clear peak, discuss possible reasons:
   - too few signal events,
   - strong background,
   - poor binning choices,
   - or simply a dataset with no resonance (this is allowed).

**Deliverables for Task 2.3:**

- Numerical estimates of $M_0$, $\Gamma$ and $\tau$ (or a justified statement that no resonance is visible).

*Note:* In realistic particle–physics measurements the intrinsic line shape of an unstable particle is described by a relativistic Breit–Wigner (a Lorentzian), whereas the observed invariant–mass distribution is typically smeared by detector resolution and may appear approximately Gaussian. Since the simplified datasets used in this project were generated with Gaussian mass fluctuations, a Gaussian fit is appropriate for extracting the central mass and width.

- Gaussian Fit of the Resonance Peak (on the histogram as a figure in pdf to include in your report)

Fit the resonance peak region with a Gaussian model,

$$f(M) = A \exp\left[-\frac{(M - M_0)^2}{2\sigma^2}\right] + B,$$

where $M_0$ is the central mass, $\sigma$ is the width parameter, and $B$ is a constant background term. From the fit, extract: the best-fit central mass $M_0$, the fitted width $\sigma$, an approximate physical width $\Gamma \approx 2.35\,\sigma$. Compare the fitted values of $M_0$ and $\Gamma$ with those estimated directly from your histogram, and comment on whether the Gaussian fit provides a more stable or precise determination of the resonance parameters.

- Optional — Breit–Wigner / Lorentzian Fit (Advanced), plot it on the histogram

As an optional extension, fit the peak region using a Breit–Wigner (Lorentzian) model,

$$BW(M) = \frac{A}{(M - M_0)^2 + (\Gamma/2)^2} + B.$$

Compare the parameters $M_0$ and $\Gamma$ obtained from the Breit–Wigner fit with those extracted from the Gaussian fit. Discuss briefly:

a. which functional form appears to describe your dataset better,

b. whether the observed peak shape is closer to Gaussian, Lorentzian, or intermediate,

c. and what this implies about detector resolution versus intrinsic resonance structure in realistic experimental conditions.

This task is optional and intended for students who wish to explore resonance line-shape

### Task 2.4 (optional but recommended): Signal significance

Choose a window around the peak (for example $M_0 \pm 2\Gamma$):

1. Estimate the number of events in the peak region $N_{\text{peak}}$.
2. Estimate the background under the peak, for example by interpolating from side-bands.
3. Define $S$ (signal) and $B$ (background) and compute a very rough significance

$$\frac{S}{\sqrt{B}}.$$

This is intentionally crude; the goal is to connect with the idea of statistical significance in particle searches.

# Part 3: Short scientific report (2–3 pages)

Write a short report in the style of a simple experimental analysis note. The length should be about 2–3 pages.

### Suggested structure

**Introduction** Briefly explain:

- what a resonance is,
- why invariant mass is the key observable,
- what theoretical tools you used (Lorentz invariance, natural units, basic decay kinematics).

**Methods** Describe:

- the structure of the dataset,
- how you computed energies and invariant masses,
- how the histogram was constructed (range, binning, any cuts),
- which software tools you used.

**Results** Present:

- the invariant mass histogram,
- your estimates of $M_0$, $\Gamma$ and $\tau$,
- (optionally) your significance estimate $S/\sqrt{B}$.

**Discussion** Interpret your findings:

- Does the distribution show convincing evidence for a resonance?
- Compare your extracted $M_0$ and $\Gamma$ to candidate particles in the PDG tables.

- Suggest at least one plausible identification of the resonance (if it exists) and discuss whether your width is compatible with PDG within the (large) experimental and methodological uncertainties of this exercise.
- Comment on possible systematic effects: binning, limited statistics, simplified decay model, etc.

**Conclusion** Summarize your main results in 5–6 sentences.

## Submission

Submit the following:

- Part 1: written answers to the conceptual questions.
- Part 2: selected intermediate results (first 10 invariant masses, histogram, numerical estimates).
- Part 3: the final report as a PDF (including figures).
- Your analysis code (Python/Matlab/Jupyter notebook, or similar), clearly commented.

**Deadline: 18-12-2025 at noon 12:00.**

**Oral presentation: 19-12-2025 at 09:00.**

**Remarks:** The datasets are generated using real resonance masses and widths, but with simplified decay channels and kinematics. Do not be surprised if the exact branching ratios do not match the PDG; focus on mass, width and the qualitative behavior of the invariant mass distribution.